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ROOF MOISTURE SURVEY. TEN STATE OF NEW HAMPSHIRE BUILDINGS,(U)
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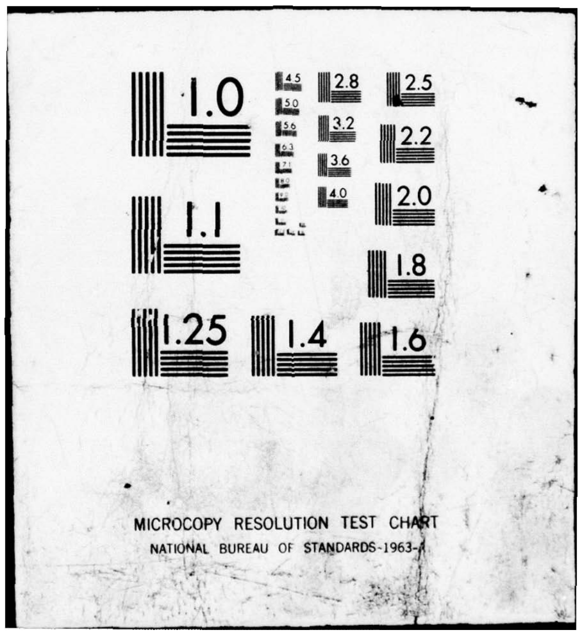
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CRREL REPORT 77-31

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Roof moisture survey

Ten State of New Hampshire buildings

Cover: Roof of State Library in Concord, New Hampshire, on 15 December 1976, with wet and dry areas marked with paint. Note frost in dry area. (Insert shows infrared camera system.)

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Roof moisture survey.

Ten State of New Hampshire buildings,

(10) W.N. Tobiasson, C.J. Korhonen [redacted] T Dudley

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Prepared for

DEPARTMENT OF PUBLIC WORKS AND HIGHWAYS
STATE OF NEW HAMPSHIRE

By

CORPS OF ENGINEERS, U.S. ARMY

COLD REGIONS RESEARCH AND ENGINEERING LABORATORY

HANOVER, NEW HAMPSHIRE

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Ten roofs in Concord, New Hampshire, were surveyed for wet insulation using a hand-held infrared camera. Suspected wet areas were marked on the roof with spray paint and roof samples were obtained to verify wet and dry conditions. Recommendations for maintenance and repair were made based on infrared findings, water contents, and visual examinations. An incremental economic study is presented to serve as a guide in determining the most cost-effective approach.

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PREFACE

This report was prepared by Wayne Tobiasson, Research Civil Engineer; Charles Korhonen, Research Civil Engineer; and Timothy Dudley, Civil Engineering Technician, Construction Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Alan Greatorex, Civil Engineering Technician, secured and compiled information used in the economic analysis presented in this report. Funding was provided by the Department of Public Works and Highways, State of New Hampshire.

Dr. H.W.C. Aamot of CRREL technically reviewed this report.

The authors are indebted to J. David Soper and Joseph O'Conner of the Public Works Division, Department of Public Works and Highways, State of New Hampshire, for assistance in developing and conducting this program.

The initiative to involve CRREL in this work was provided by Robert Cox of the New England Innovation Group (NEIG), Providence, Rhode Island. The objective of NEIG is to better utilize technology by "creating new partnerships between Federal, State and local governments and the technology community." The authors appreciate the interest NEIG has shown in this technology.

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4*	millimeter
foot	0.3048*	meter
pound/inch^2 (gage)	6.894757	kilopascal
pound/foot^3	16.01846	kilogram/meter^3
British thermal unit	1055.056	joule
Btu/foot^2	11356.53	joule/meter^2
Btu/pound	2326.000*	joule/kilogram
ft^2 h °F/Btu	0.1761102	m^2 K/W
degrees Fahrenheit	$t_{°C} = (t_{°F} - 32)/1.8$	degrees Celsius

* Exact

ROOF MOISTURE SURVEY: TEN STATE OF NEW HAMPSHIRE BUILDINGS

W.N. Tobiasson, C.J. Korhonen and T.J. Dudley

INTRODUCTION

During the evenings of 13 and 14 December 1976 the following State buildings in Concord, New Hampshire, were surveyed with an infrared camera to locate wet roof insulation:

1. State House
2. State House Annex
3. State Library
4. Legislative Office Building
5. Public Health Complex (South Spring Street)
6. Highway Garage
7. Fish and Game Offices
8. Supreme Court
9. John O. Morton Building
10. Department of Health and Welfare Laboratory.

Infrared photographs (thermograms) were obtained of light-colored (hot) anomalies on each roof. Suspected moisture-caused anomalies were outlined in white spray paint (see cover photograph of State Library roof). During daylight hours from 13 through 16 December visual examinations were made of the roofs, flaws were marked with spray paint, conventional photographs were obtained, and problem areas were dimensioned. Samples were taken of wet and dry areas to verify findings with the infrared camera.

INFRARED CAMERA

The AGA Thermovision 750 infrared camera used for these surveys is shown in Figure 1. The camera measures energy radiated by a surface in the 2 to 5.6 μm portion of the electromagnetic spectrum. The camera converts this energy to gray tones and displays them on a cathode ray tube viewing screen in the display unit. A spinning prism in the camera creates 25 pictures per second on the viewing screen. The resulting real-time thermal image is similar to that presented on an aged and somewhat poorly adjusted black and white television. By moving the camera about and viewing the screen, as shown in Figure 1, a roof can be examined in detail. The Polaroid attachment can be used to obtain a conventional Polaroid photograph of the image on the viewing screen. Such photographs are termed thermograms.

Different tones on a thermogram denote differences in the *apparent* surface temperature of all objects in view. The adjective "apparent" is necessary since the amount of electromagnetic radiation emitted by a surface (i.e. the brightness of its image on the thermogram) is not just a function of its temperature but also of its ability to emit heat by radiation. This property of the surface is termed emissivity. If two objects have the same surface temperature but different emissivities, the object with the higher emissivity will appear brighter on the viewing screen. If two objects have the same emissivity, the one that is warmer will emit more electromagnetic radiation and appear brighter on the viewing screen.

Like a television, the infrared camera has a brightness control which can be used to vary the image on the screen from bright through varying degrees of contrast to dark. The camera is adjusted to give a middle tone (not bright, not dark) to the roof and a search is made for brighter areas. During the search it is quite easy to see drains, vents and other appurtenances on the viewing screen since their apparent surface temperature is not identical to that of the roof because of temperature and/or emissivity differences.

Fortunately the emissivity variations over a conventional roof membrane (either gravel-covered or bare) are minor. Bright portions of a membrane as seen by the infrared camera are usually caused by temperature differences. Where roof insulation is wet, heat from the building passes out through the roof faster than normal. This warms the surface of the membrane in that area and a bright anomaly appears on the viewing screen. In

Figure 1. AGA Thermovision 750 camera system: 1) camera, 2) display unit, 3) Polaroid camera, 4) battery pack.

this manner, wet insulation is located with an infrared camera. However, not all bright spots are related to wet roof insulation. For example, the roof above a boiler room will probably be hotter (brighter on the viewing screen) than adjacent roof areas. A heater suspended just below the ceiling can have the same effect. The hot exhaust from roof-mounted fans often warms areas on a roof. The infrared camera sees all of these as bright anomalies. It takes a fair amount of experience to determine the cause of each hot spot and to isolate those which are potentially moisture-caused. Only those anomalies thought to be moisture-caused are outlined in white spray paint.

Daytime roof moisture surveys with the AGA camera are of little value since solar effects mask temperature differences caused by entrapped moisture. Consequently all thermograms presented in this report were taken at night.

CORE SAMPLES

To verify infrared findings, several cores were taken of the roof membrane and insulation at locations expected to be wet and others expected to be dry. A spudding bar (effectively a 4-ft-long chisel) was used to dislodge the gravel from a 12-in.×12-in. area of the membrane. Three-in.-diam samples were obtained in the center of each cleared area using the CRREL-designed roof sampler shown in Figure 2. The samples were sealed in plastic bags and later weighed, dried at 110°F and reweighed to determine the amount of water present. Water contents discussed in this report are expressed in percentages as the weight ratios of water to dry insulation.

CRREL provided 2¾-in.-diam expanded polystyrene plugs to fill each hole after a sample was taken. The New Hampshire Department of Public Works and Highways arranged for qualified roofers to insert these plugs in a bed of roofing cement and to patch the membrane after each sample was taken. The bonding companies involved require that these expedient patches be removed at a later date and a 12-in.×12-in. section of the membrane be patched. Arrangements for this work are being handled by the Department of Public Works and Highways.

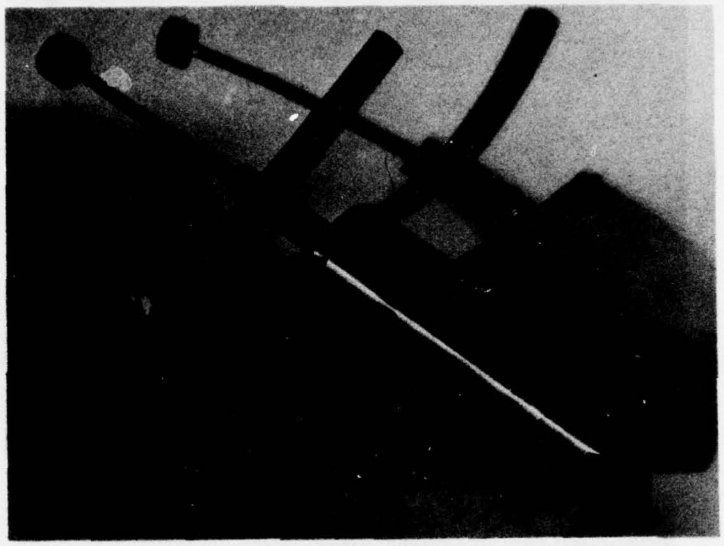


Figure 2. CRREL roof sampler was used to obtain 3-in.-diam cores of membrane and insulation.

STATE HOUSE

This roof appeared somewhat mottled when viewed through the infrared camera. Past surveys on many roofs indicate that mottling represents a nonuniform dampness of the insulation. There were no bright* well-defined anomalies, but one rectangular area on the roof was noticeably darker than its surroundings. A thermogram of that area is shown in Figure 3 and its location is shown on the roof plan (Fig. 4). The well-defined rectangular nature of this anomaly and its darkness suggest it is not moisture related. Locations for sampling were marked in the center of the dark area and the adjacent mottled area (W and X respectively in Fig. 3 and 4). When sampling plans were discussed with State representatives, it was learned that there is no insulation under the membrane of this roof. Since there is no insulation, no samples were obtained. A visual inspection of this roof revealed that the gravel-covered membrane was in good condition. Two flashing flaws were detected along the parapets where shown in Figure 4. They were marked with white spray paint and should be repaired. A mass of bitumen had been applied in an attempt to repair one of these flaws but new cracks have developed in that patch. It is probably not economically feasible to remove and replace this membrane for the sole purpose of adding insulation to this thermally poor roof. When, in due course, this membrane is no longer serviceable and must be replaced, insulation should be added to reduce heat losses.

STATE HOUSE ANNEX

This roof also appeared mottled when viewed through the infrared camera. A thermogram which shows this feature is presented in Figure 5. A photograph of the same area is shown in Figure 6. A plan view of the roof is shown in Figure 7. A small rectangular area about 2×4 ft showed up as a bright anomaly. It was outlined in white spray paint and sampling points O and P were established there as shown in Figure 8.

The following day the roof was sampled at locations O, P, Q, and S (Fig. 7). No insulation was present between the membrane and the deck. At point O, within the bright rectangular anomaly (Fig. 7), membrane plies were not well bonded and they delaminated easily. A layer of ice, $^1/_2$ in. thick, was present under the $^3/_8$-in.-thick membrane as shown in Figure 9. A solid concrete deck was present below the ice. Chips of the concrete were found to have a density of 130 lb/ft^3. Because of the unusual findings at point O, additional samples were taken on this roof. Nearby at point P (Fig. 8) no ice was found. However, $4^1/_8$ in. of granular fill resembling clinkers was present between the membrane and the deck. The top surface of the clinker layer

* Like a television, the infrared camera has a brightness control that can be used to vary the image on the screen from white through varying degrees of contrast to black. When terms such as dark or bright are used in this report they refer to relative conditions over the roof being studied.

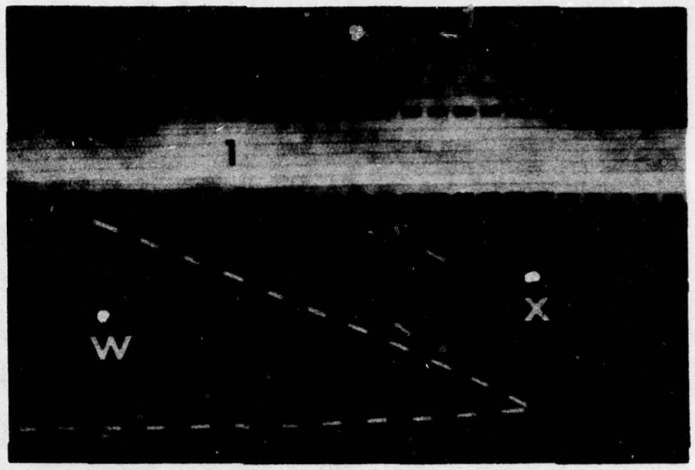


Figure 3. Thermogram of dark rectangular area, State House (1 – parapet). Dashed white line separates dark and mottled anomalous areas; letters refer to sampling sites.

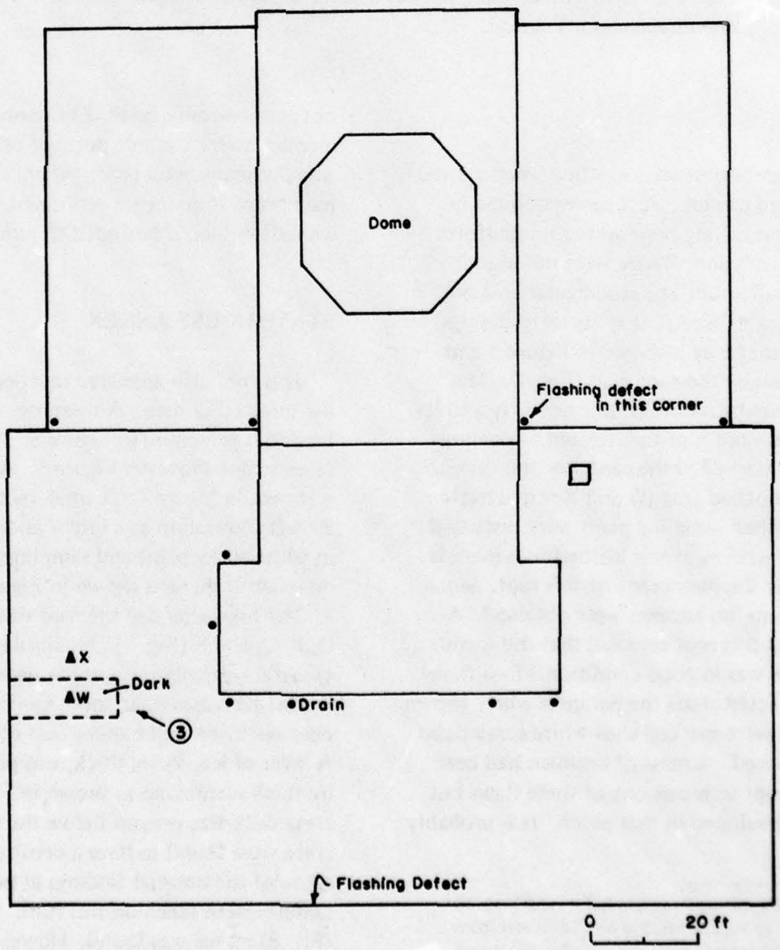


Figure 4. Plan view of State House roof. Circle and arrow indicate location and viewing direction of Figure 3.

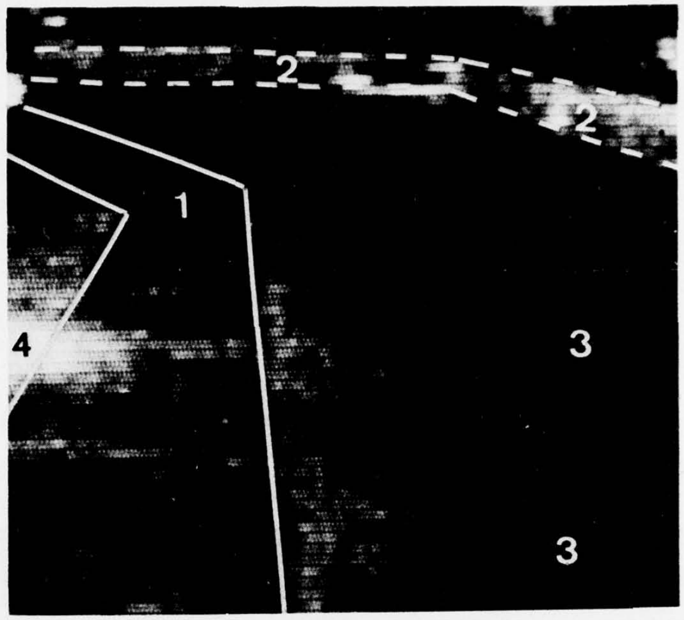


Figure 5. Thermogram showing mottled appearance of the State House Annex roof (1 – walkway, 2 – parapet, 3 – patches of ice, 4 – heat from exhaust fan).

Figure 6. Photograph of the area shown in Figure 5.

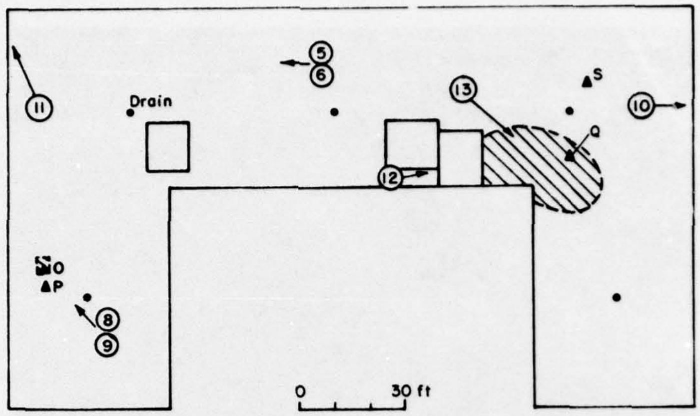


Figure 7. Plan view of the State House Annex roof. Circles and arrows indicate location and viewing direction of Figures 5, 6, and 8-13.

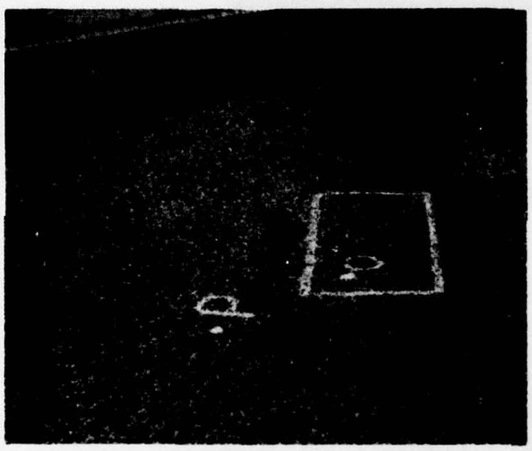


Figure 8. Outline of bright rectangular anomaly showing sample locations O and P.

Figure 9. Ice ½ in. thick was present under the membrane at point O.

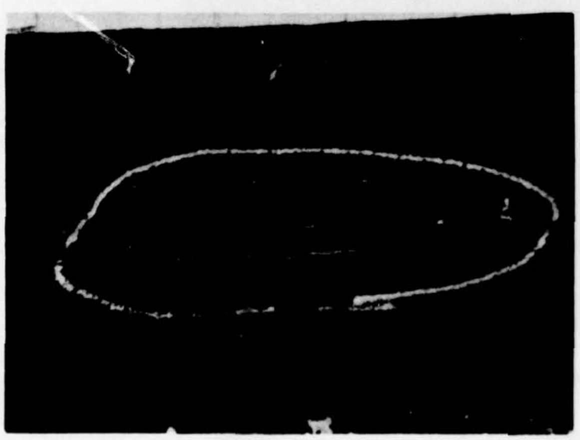


Figure 10. Flashing split circled in white spray paint. Fifteen such splits were located around the perimeter of this roof.

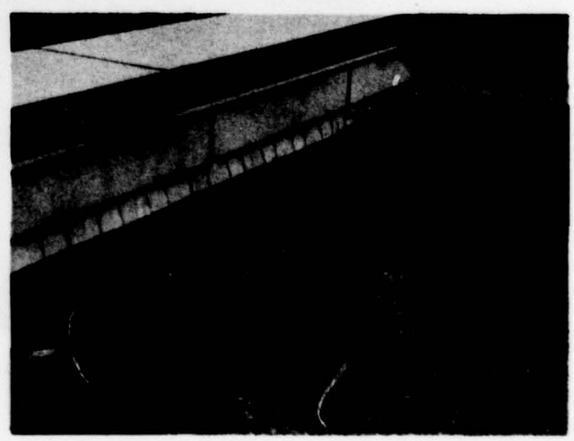


Figure 11. Damaged parapet wall counter flashing.

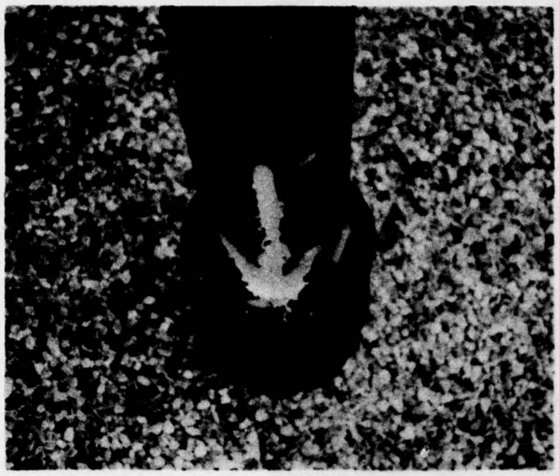


Figure 12. Cracked bitumen in a pitch pocket surrounding a vent pipe.

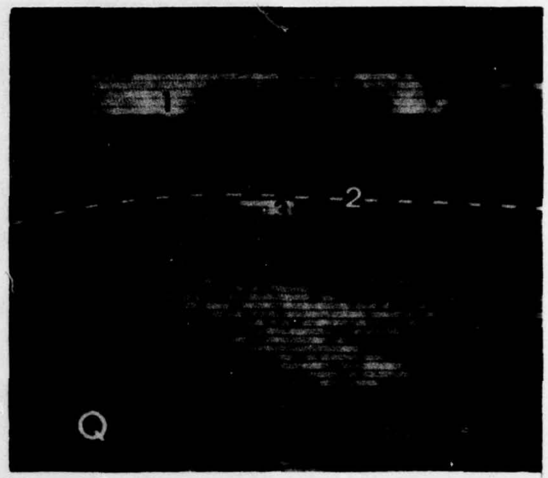


Figure 13. Thermogram of egg-shaped anomaly on the State House Annex roof (1 – parapet, 2 – boundary of anomaly, 3 – rectangular pitch pocket on roof).

was lightly bonded with mortar to form a smooth substrate for the membrane. The clinkers were relatively dry, having a water content of only 4%. In the past, clinkers were used to provide slope for drainage of flat decks. The source of the ice at point O is not apparent. However, the deteriorated flashing around the building indicates that numerous points are available where water could get in under the membrane. Examples of flashing problems on this roof are shown in Figures 10 and 11. Other entry points for moisture are also present as shown in Figure 12. Portions of the roof are blistered.

A larger, egg-shaped anomaly was also detected with the infrared camera (Fig. 13). It did not have a well-defined boundary as did the rectangular anomaly previously discussed nor was it as uniformly bright. A dashed line of white spray paint was used to approximate its extent (Fig. 7). At S the membrane was in good condition but at Q the membrane was brittle, dry and easily delaminated. No insulation was present under the membrane at either Q or S. S was in a mottled area similar to the area in Figure 5. The water content of chips of the concrete deck at points Q and S was determined to be 9% and 15%, respectively. It is likely that such differences in deck moisture explain the surface temperature differences seen by the infrared camera over most of this roof. Moisture in the concrete deck decreases its insulating value.

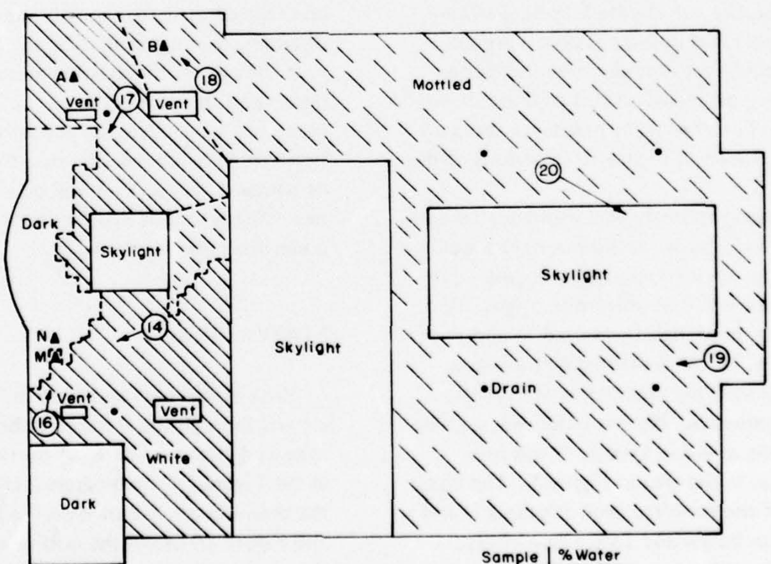
Although a large portion of the roof membrane was expected to be delaminated and brittle, this roof was not considered to be particularly problematic. However, because of its aged condition, problems are expected in the future. Such problems can be delayed somewhat by patching the numerous flashing flaws and eliminating other visible defects where water can enter the membrane.

It is probably not economically feasible to remove and replace the entire membrane for the sole purpose of adding thermal insulation to this thermally poor roof. However, the existing membrane is in poor condition and the deck is damp. Before long a new membrane will be needed and at that time substantial insulation should be added. Because the deck will quite likely be damp at that time, it will be important to design a new system so that this moisture will not be trapped under the new membrane.

STATE LIBRARY

Most of this roof appeared mottled or white when viewed through the infrared camera. Only one area appeared relatively dark. A portion of this area is shown in the Figure 14 thermogram. The viewing direction of the thermogram is shown on the roof plan (Fig. 15), and Figure 16 shows the outline of the dark area in the thermogram from a different viewing direction. Early on the cold morning of 15 December the area within the spray painted boundary was covered with frost as shown in Figure 17. The remainder of the roof contained wetter insulation which permitted more rapid flow of heat through the building there. Consequently, the surface was too warm for frost to form on that portion of the roof. It was gratifying to see that the naturally

Figure 14. Thermogram showing a portion of the only dark area on the State Library roof (1 – parapet).



Sample	% Water
A	261
B	239
M	211
N	32

Figure 15. Plan view, State Library roof. Circles and arrows indicate locations and viewing directions of Figures 14 and 16-20.

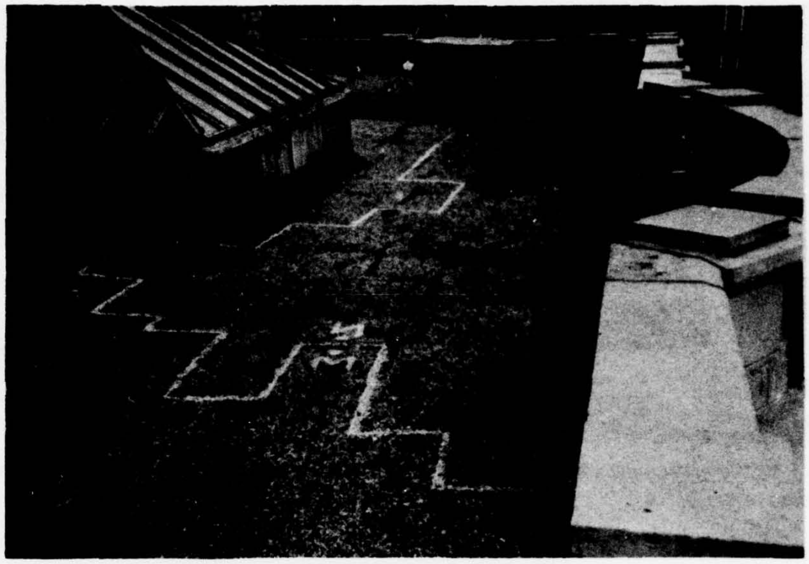


Figure 16. The area outlined in spray paint appeared darker than all other portions of the State Library roof.

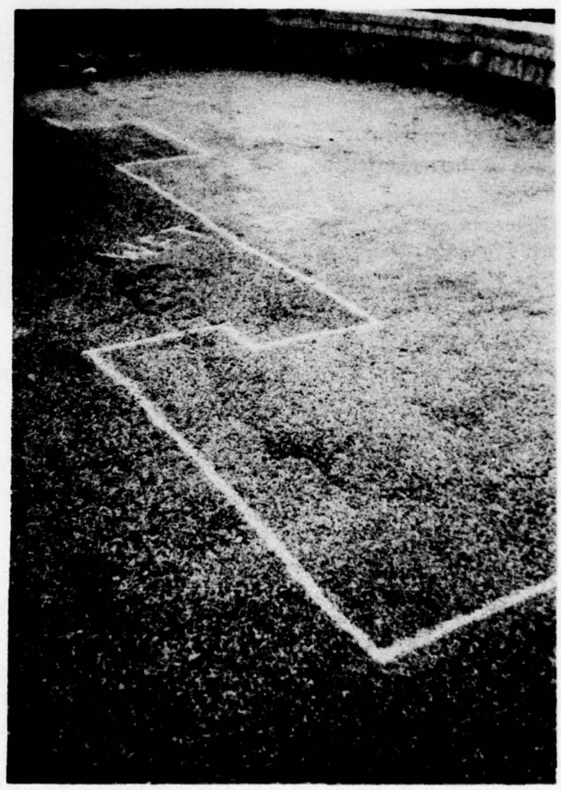


Figure 17. The spray painted area coincided with the area on which frost formed. This was the driest portion of the roof but the insulation contained enough moisture (32%) to reduce its thermal effectiveness over dry insulation.

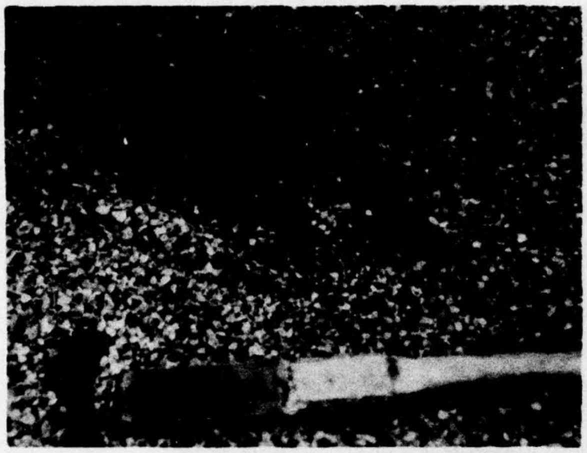


Figure 18. The dry brittle membrane was easily damaged during spudding of gravel.

Figure 19. Large blisters on the State Library roof.

occurring wet-dry boundary coincided with that defined by using the infrared camera two nights before.

The spray painted boundary in Figure 16 was stepped since it follows the edges of board stock insulation. Core samples of the $1\frac{1}{8}$-in.-thick wood fiber insulation at N and M had water contents of 32% and 211% respectively. Although insulation in the area represented by sample N was much drier than that of the rest of the roof, it contained enough moisture (32%) to seriously reduce its thermal effectiveness.

The membrane was severely deteriorated. Spudding of the gravel had broken apart the dry, brittle membrane (Fig. 18). A qualified roofer carefully patched the membrane after this photograph was taken.

Insulation samples taken at A and B (Fig. 15) had water contents of 261% and 239%, respectively.

Long blisters were present over much of the roof as shown in Figure 19. Since this area had about the same brightness on the infrared camera as the area where sample B was taken, it is also expected to contain some wet insulation.

All of the insulation on this roof was either damp or wet and the membrane was dry, brittle and obviously not water-tight. Consequently the membrane and insulation should be removed and new insulation and a new membrane installed. Because the deck below the wet insulation is probably wet, it will be important to ventilate the new system to prevent trapped moisture from destroying the new membrane.

Skylight caulking was in bad condition (Fig. 20). Ample opportunities exist for water to enter the roof from that area. Major improvements to better seal the skylights will be required in conjunction with new roofing.

Figure 20. Skylight caulking needs repair.

The economics of replacing the membrane and insulation of this roof will be discussed in a subsequent section of this report.

LEGISLATIVE OFFICE BUILDING

The old Post Office section of the Legislative Office Building contains steeply pitched slate roofs which were not surveyed. The small flat roof above the sloped roofs is uninsulated, according to State representatives. The new portion of the Legislative Office Building contains built-up roofing which was comprehensively examined with the infrared camera. No thermal anomalies were detected. The roof appeared to be in excellent condition except that, at about 30 locations around the

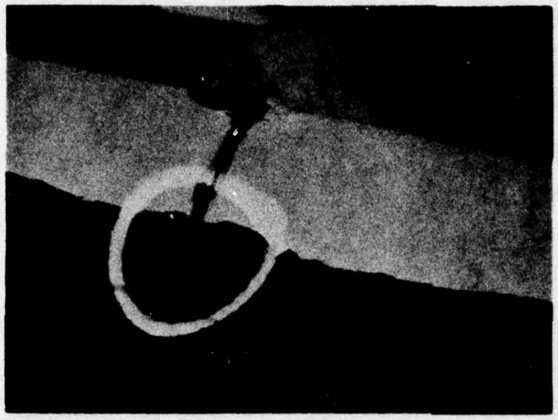


Figure 21. Mastic between the pieces of metal fascia has been split by thermal movements of the fascia, Legislative Office Building.

perimeter, movements of the sectional metal fascia had split the mastic at joints (Fig. 21). These locations were circled in white spray paint. In a few areas the splits extended down to the level of the gravel on the built-up membrane. A more reliable method of sealing the fascia should be devised to prevent entry of unwanted moisture and rapid deterioration of this currently excellent roof.

PUBLIC HEALTH COMPLEX

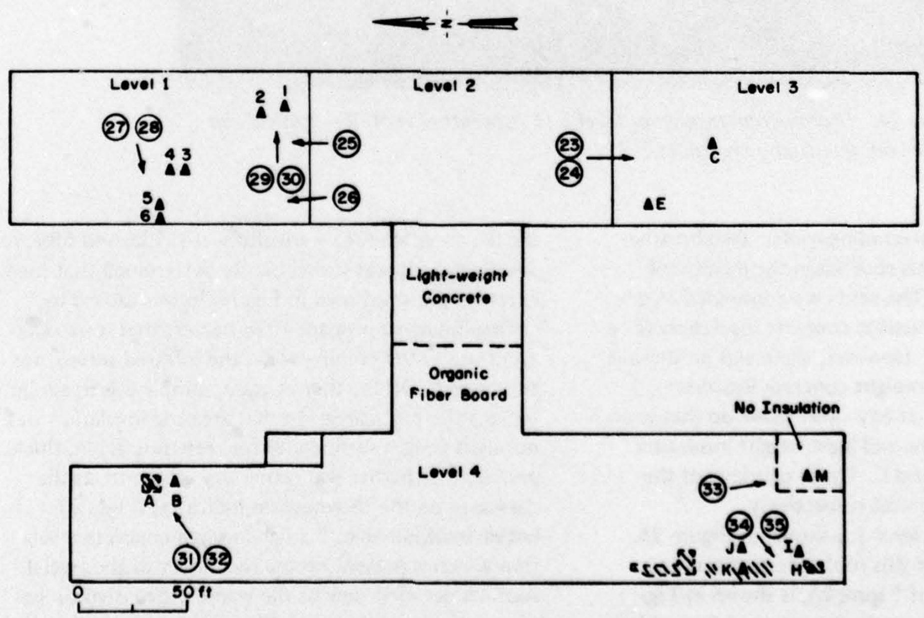
The two levels of flat gravel covered built-up roofs on the Public Health Complex were examined with the infrared camera. No thermal anomalies were detected. Visual examination did not uncover any obvious roof defects.

HIGHWAY GARAGE

The roof of the Highway Garage was thermally complex. Four levels are present as indicated on the roof plan (Fig. 22). All levels are relatively flat with ridges along their centerline that provide slope sufficient to drain water to the eaves or to scuppers along the eaves. It is understood that the gravel-covered membrane is only a few years old.

Level 2, the highest area, harbored no thermal anomalies and was visually in good condition.

A panoramic view of *level 3* was attained from level 2 (Fig. 23). A three-thermogram mosaic was also obtained from the same position (Fig. 24). The thermogram mosaic is mottled, fairly bright and contains dark lines which span the width of the roof. Large concrete beams under the roof insulation are the cause of the dark lines. They have caused the roof directly above



Sample	% Water
A	130
B	28
C	32
E	40
H	227
I	28
J	6
K	158
M	No Insulation
3	62
4	113
5	68
6	5

Figure 22. Plan view of the Highway Garage roofs. Samples were not taken at locations 1 and 2.

Figure 23. View of level 3, Highway Garage (1 – breather vents, 2 – typical cap where concrete frame protrudes).

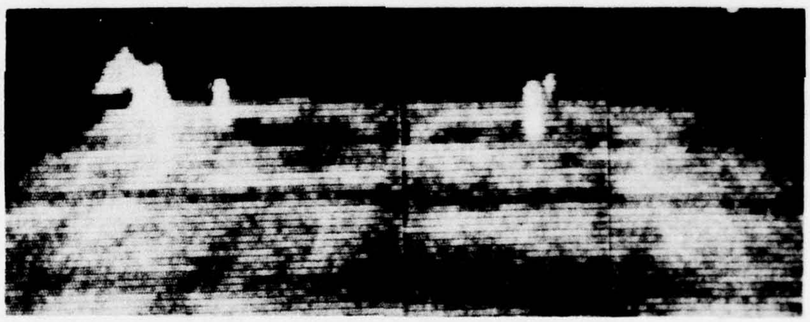


Figure 24. Thermogram mosaic of level 3 (1 – breather vent, 2 – typical cap where concrete frame protrudes).

to be colder than the surrounding roofs. Two breather vents were installed in this roof when the membrane was replaced (Fig. 23). The vents were intended to dry out the light-weight vermiculite concrete insulation since it was known to be wet. However, there was no thermal indication that the light-weight concrete was drier around those vents than at any other place on that roof. Samples of the membrane and light-weight insulation were taken at points C and E. Water contents of the insulation were 32% and 40% respectively.

A panoramic view of *level 1* is shown in Figure 25. A thermogram mosaic of this roof, which covers the area in the left portion of Figure 25, is shown in Figure 26. The thermogram strongly suggested that white portions of the roof are wet. Sample 3 was wet (62%) as expected, but samples 4 and 5 in the dark area of the thermogram (26) were also wet (113% and 68%, respectively). It was subsequently determined that the extra brightness shown in Figure 26 was caused by ceiling-mounted propane-fired heaters that were operating late in the evening when the infrared survey was conducted. On the thermogram, sample 6 is in a long rectangular black area. In that area the insulation was not light-weight vermiculite concrete but 2¼-in.-thick perlite. The perlite was rather dry (5%) and, as the dark area on the thermogram indicates, it was a far better insulator than the light-weight concrete insulation which is present on the remainder of the level 1 roof. A detailed view of the well-defined division between the thermal image of the dry perlite and the wet light-weight concrete is shown in Figures 27 and 28.

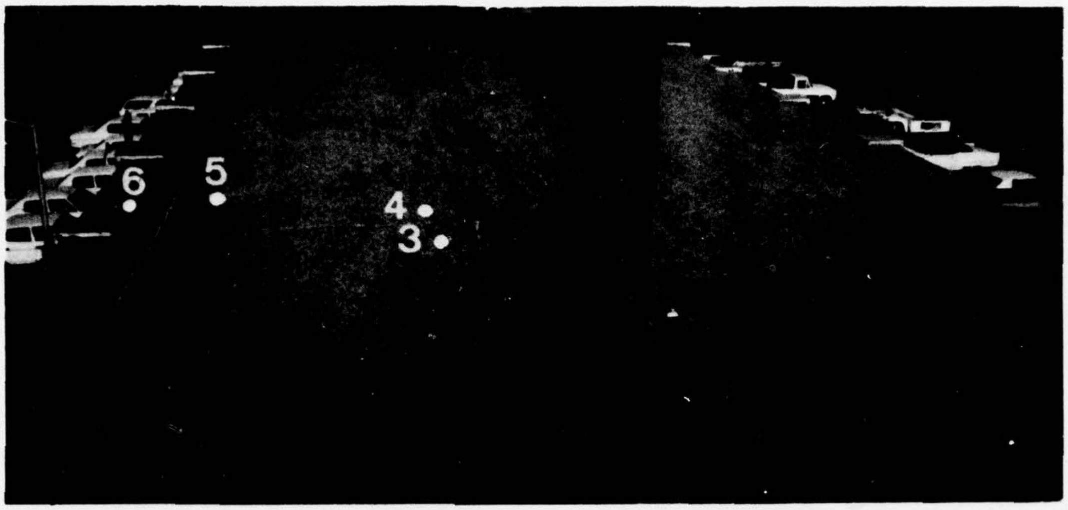


Figure 25. View of level 1, Highway Garage. Points 3-6 are sample locations.

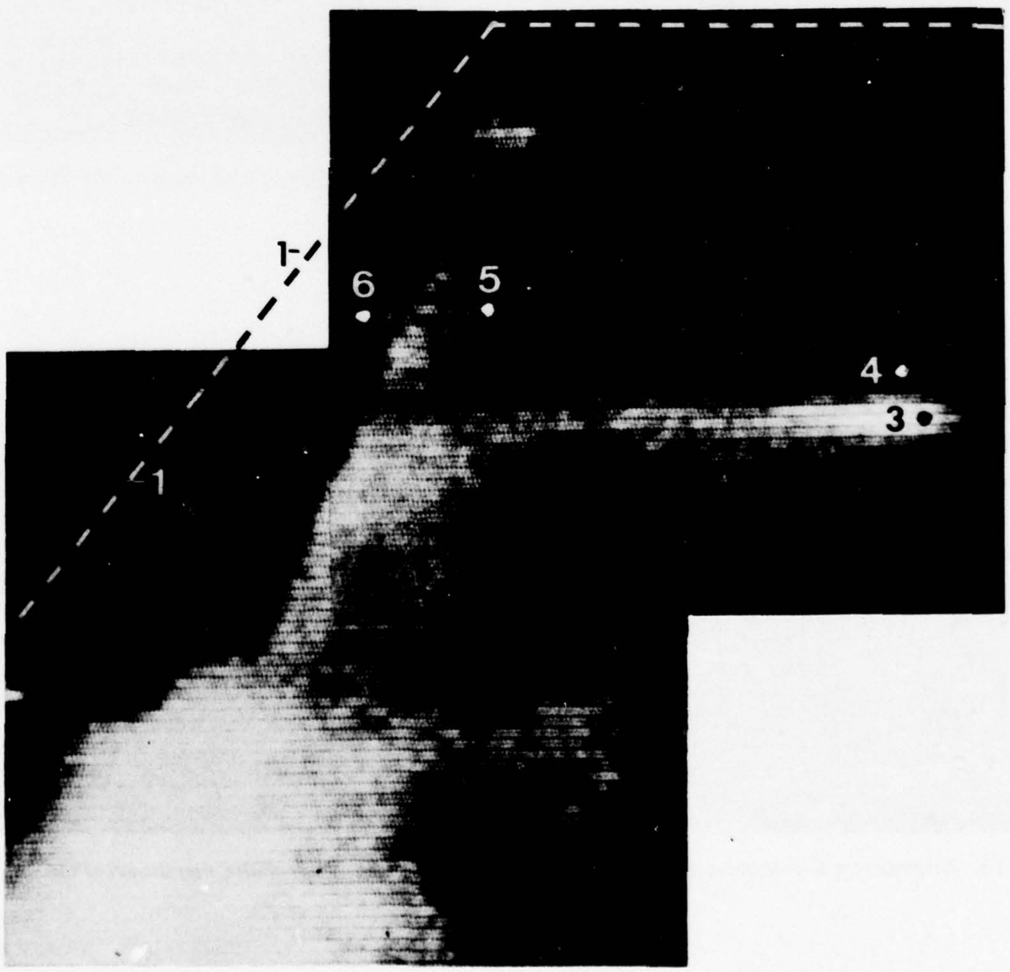


Figure 26. Thermogram mosaic of a portion of level 1. Points 3-6 are sample locations (1 — edge of roof).

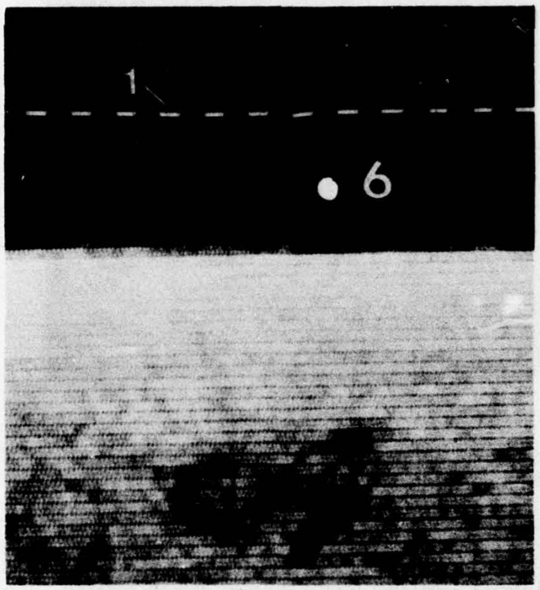


Figure 27. Thermogram of the boundary of light-weight concrete (bright area in foreground) and perlite board insulation (dark area in background) (1 – edge of roof).

Figure 28. View of area shown in the Figure 27 thermogram.

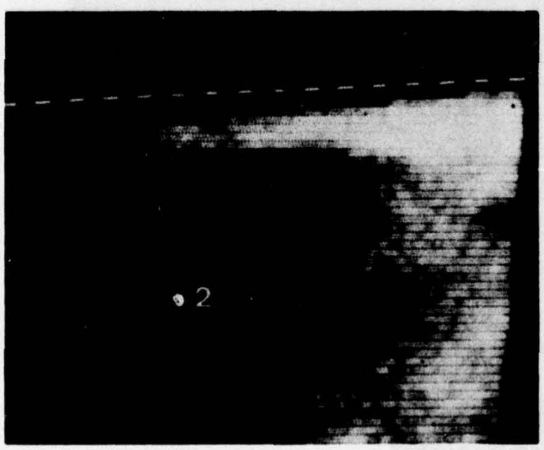


Figure 29. Thermogram of southeast corner of level 1.

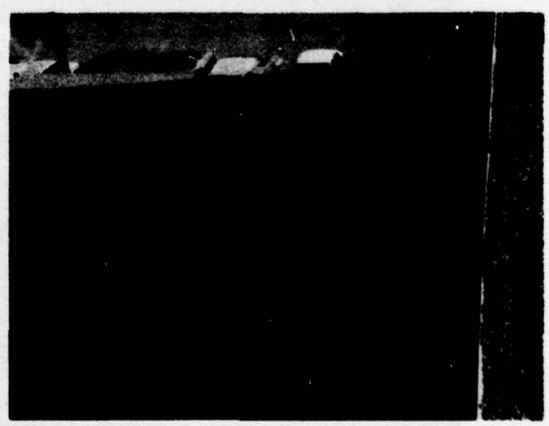


Figure 30. View of the area shown in the Figure 29 thermogram.

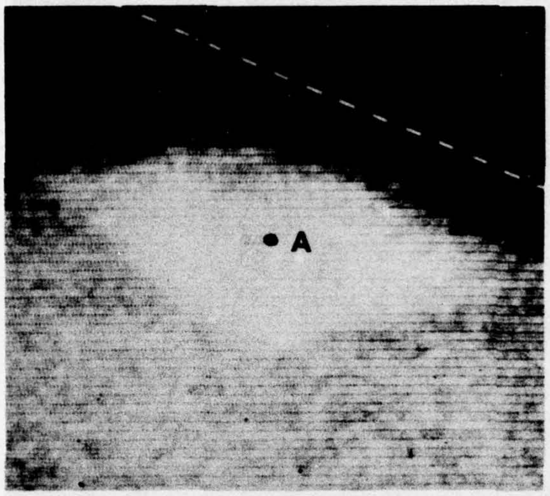


Figure 31. Thermogram of a small white anomaly near the northeast corner of level 4. Sample B was taken just beyond the thermogram's lower right corner.

Figure 32. View of the area shown in the Figure 31 thermogram.

Another thermal anomaly was detected by the infrared camera in the southeast corner of the level 1 roof, as shown in Figure 29. A conventional photograph of the same area is shown in Figure 30. It is believed that this anomaly is also related to propane-fired heaters suspended under the concrete deck. However, it is expected that the insulating concrete is wet throughout the area shown in Figure 29.

No evidence was detected to indicate that the two breather vents installed on the level 1 roof (Fig. 25) have dried the insulating concrete.

Although this level of the roof contains a large amount of moisture, it is apparently not causing problems to the occupants. Sometime before leaks develop to the point where equipment is in jeopardy or habitation of the building is impaired, a new roof will be needed.

In plan view, the Highway Garage looks like an H (Fig. 22). Half the portion of level 4 that forms the center of the H is insulated with light-weight concrete. The remainder of level 4 is insulated with organic fiberboards. The boundary of these two different insulations was marked with white spray paint. From within the building it was noticed that the structural framing method also changes at this point.

Near the northeast end of the level 4 roof, a small white anomaly was detected. A thermogram and a conventional photograph of this area are presented in Figures 31 and 32, respectively. Water contents of the insulation at A and B were 130% and 28% respectively. At A the insulation was wet, black, decomposed and compressed to a thickness of about ¼ in. At B the insulation was damp, light in color and ¾ in. thick. Based on the infrared survey, it is expected that the insulation at B represents the general condition over most of the roof in that area. Since the moisture content at B is rather high (28%), the insulation cannot be very effective thermally.

The level 4 membrane is about ¾ in. thick. It is a composite of at least two membranes of different ages.

At the southeast corner of level 4, a 26-×34-ft bright area was detected (Fig. 33). Sample M, taken where shown on the thermogram, revealed that this area was without roof insulation. In Figure 33, the bright white stripe which crosses the uninsulated area is caused by the concrete beam below that area. Such bright lines were visible all along the level 4 roof at intervals that coincided with the reinforced concrete members that support this roof. A second such stripe is also visible in the foreground in Figure 33.

Several wet areas were found along the southerly portion of the west edge of level 4 (Fig. 22). A thermogram and a conventional photograph taken of one of the anomalies in this area are shown in Figures 34 and 35. Sample H, taken within the bright area of the thermogram, had a water content of 227%. Sample I, taken in the darker region nearby (Fig. 35), had a water content of 28%. No visible signs of membrane or flashing distress were evident in this area. Rainwater drains over a gravel stop at the eaves all along the nearby edge. It is speculated that snow meltwater, backed up on the roof by slight icings at the eave during the winter, found

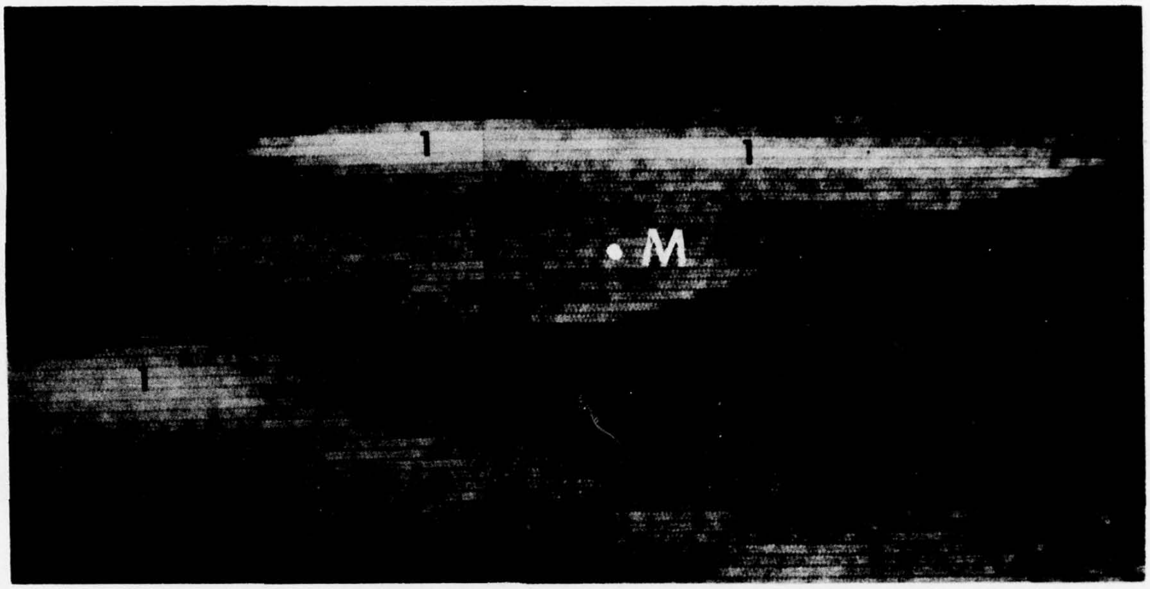


Figure 33. Thermogram of the uninsulated area in the southeast corner of level 4 (1 — hot bands above concrete beams).

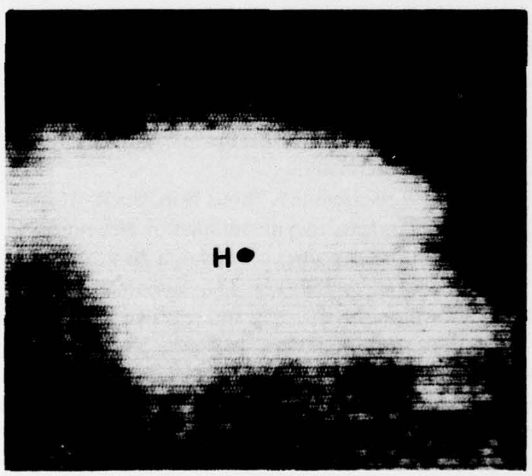


Figure 34. Thermogram of the anomaly in the southwest corner of level 4. Sample I was taken just beyond the lower left corner of the thermogram in the gray area.

Figure 35. View of area shown in the Figure 34 thermogram.

its way into the roof through membrane flaws in this area. Over the eave drainage of essentially flat roofs in cold regions is seldom a problem-free situation.

Samples J and K were taken nearby as shown in Figure 22. Water contents were 6% and 158%, respectively, further verifying the infrared findings.

The level 4 roof is poorly insulated and has localized moisture problems which are expected to worsen rapidly. Although there is apparently no urgency to replace this roof because serious leaks are not present, a new roof and a significant amount of insulation should be considered before long.

Economic questions associated with the removal and replacement of the four roofs of the Highway Garage and the provision of additional thermal insulation will be discussed in a subsequent section of this report.

FISH AND GAME OFFICES

A regular pattern of white spots and lines was detected by the infrared camera on a portion of the lower roof (Fig. 36). A photograph of the same area shown in the Figure 36 thermogram is presented in Figure 37. Arrows on the plan view of this roof (Fig. 38) show the portion of this roof viewed in those two figures. A photograph taken inside the building in the same area (Fig. 39) shows that the spots on the thermogram are located above the ceiling-mounted light fixtures and that the bright lines are above the beams which support the wooden joists of this roof. Glass fiber insulation is present between the joists above the suspended ceiling. No continuous vapor barrier is present on the warm side of this insulation. Samples A and B (Fig. 38) revealed that the gravel-covered membrane is very brittle. It is supported directly on wood decking; all roof insulation is in the joist spaces below. Chips of the wood deck taken at A and B had water contents of 6% and 10% respectively.

A second thermogram of the lower roof (Fig. 40), taken where indicated in Figure 38, also showed a regular pattern of stripes which were found to lay above structural members of the roof. Apparently the glass fiber insulation batts were not placed tight to the end of joists above these members, and thermal weak links developed which show up on the thermogram.

The membrane is in poor condition. Since the deck and joists are wood, serious deterioration of structural members could easily occur if leaks develop.

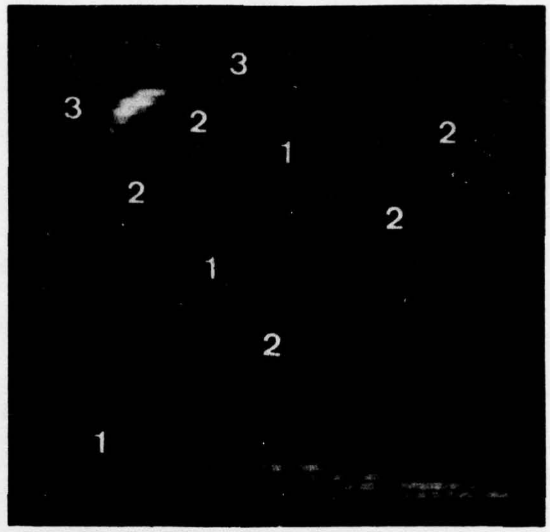


Figure 36. Thermogram taken on lower roof showing a regular pattern of stripes (1) and spots (2). The parapet is denoted by (3).

The lower roof has one internal drain. Stains in the gravel and moss growing on the roof suggest that complete drainage is not achieved. Perhaps some water ponded on this roof from time to time has entered the membrane and accelerated its deterioration. However, the lack of a continuous vapor barrier within the building also permits warm moist inside air to reach the underside of the membrane and cause deterioration.

Figure 37. View of the area shown in the Figure 36 thermogram.

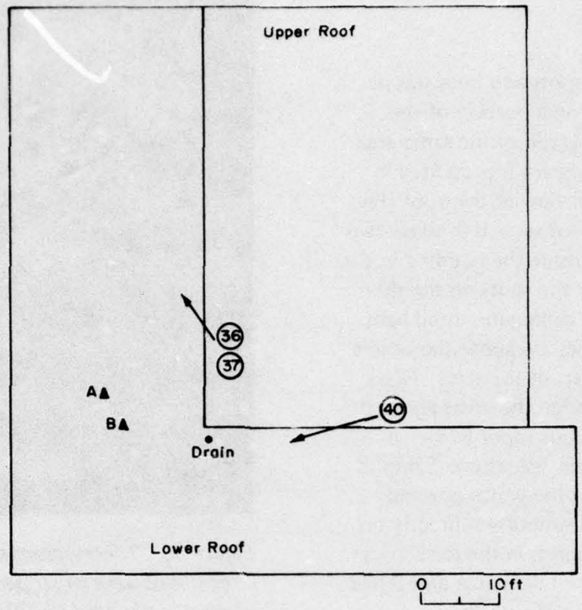


Figure 38. Plan view of the roofs of the Fish and Game offices.

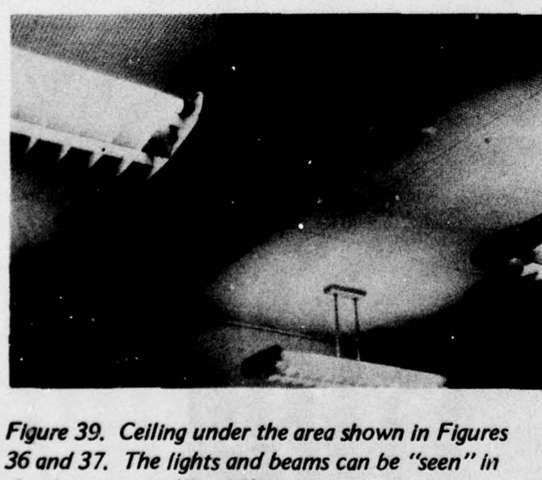


Figure 39. Ceiling under the area shown in Figures 36 and 37. The lights and beams can be "seen" in the thermogram (Fig. 36).

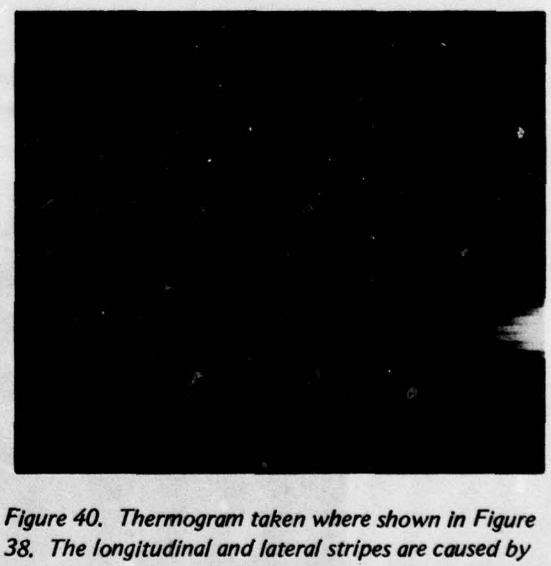


Figure 40. Thermogram taken where shown in Figure 38. The longitudinal and lateral stripes are caused by weak thermal links above the members that support this roof. The white spot at the right edge of the thermogram surrounds the only drain on this roof.

The upper roof was also surveyed with the infrared camera. No anomalies were detected. The membrane looks similar to that on the lower roof except it drains over a gravel stop at one end, not to an internal drain.

When the membrane on this building is replaced, it is suggested that internal vapor control be improved and an inch or more of board insulation be added above the wood deck to provide a more stable substrate for the new membrane.

SUPREME COURT

Except for two rectangular flat areas all portions of this roof are steeply sloped. The two flat areas are outlined in Figure 41.

Infrared surveys, conducted on the two flat areas, revealed one anomaly. It is the cross-hatched area in Figure 41. It is understood that no insulation exists between the wood deck and the membrane of this roof. Consequently no samples were taken. The rectangular nature of the anomaly suggests that it is related to a thermal feature built into the structure. However, water may have seeped into the wood deck below the membrane. This area should be examined in detail by the Public Works Division from within the building.

As shown in Figure 41, two ice ponds were present on this roof during our survey. It is not considered economically feasible to modify the two flat portions of the Supreme Court roof to better facilitate drainage. Since water and ice accelerate the deterioration of roof membranes, ponding should be avoided in future construction by providing adequate slope for drainage even on small areas, such as the two flat roofs of the Supreme Court.

JOHN O. MORTON BUILDING

This building is roofed with 1 in. of glass fiber insulation and a gravel-covered built-up membrane. A comprehensive infrared survey and a visual inspection revealed that the insulation, membrane, flashing and associated penetrations are in good condition except in two areas. These two problem areas are shown in the plan view of this roof (Fig. 42). A thermogram and photograph of the area adjacent to the penthouse are presented in Figures 43 and 44, respectively. Sample I, taken within the bright area of the thermogram, had a water content of 377%. Sample H, taken nearby (Fig. 42), had a water content of 1%. Although no obvious flashing flaws could be detected along the penthouse, it is suspected that the problem originated there.

It is recommended that the insulation and membrane in the wet area (within the spray painted boundary shown in Fig. 44) be removed and replaced with dry insulation and a new membrane. Rather than following

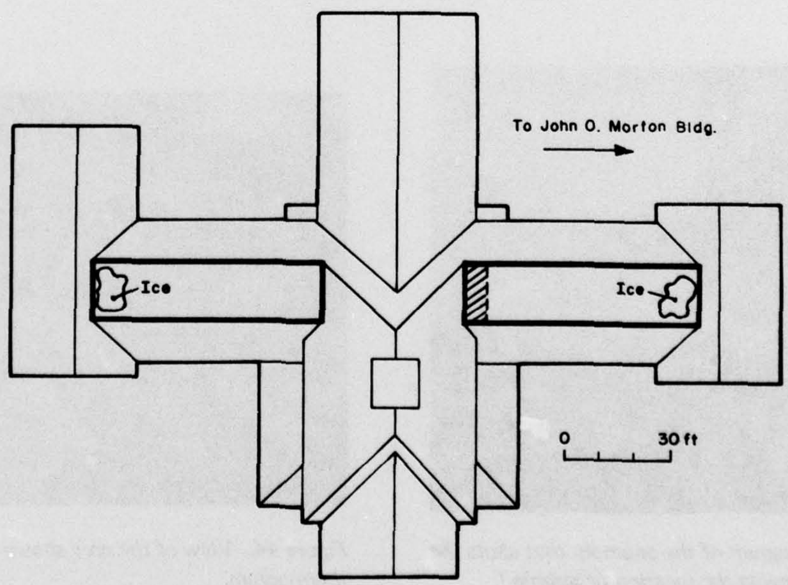
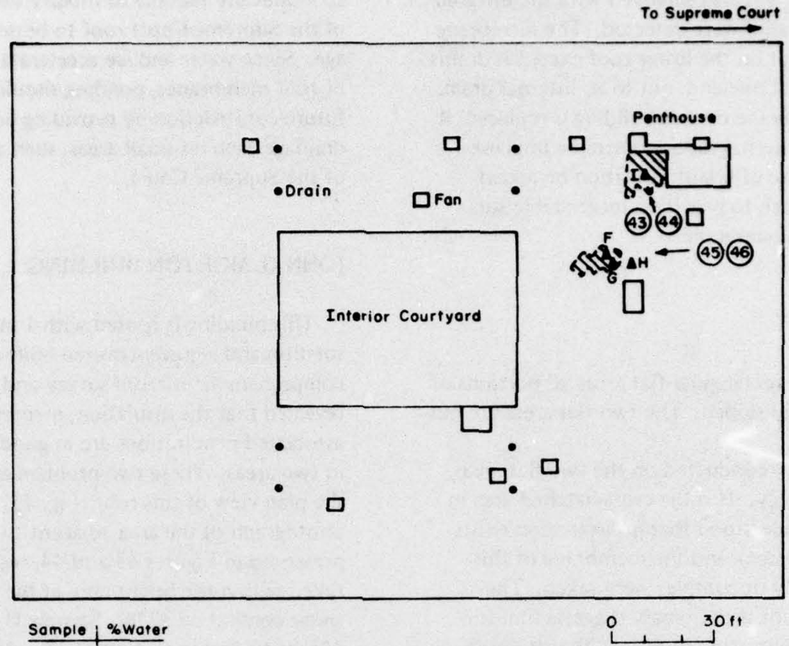


Figure 41. Plan view of the Supreme Court with the outline of the two flat built-up roofs emphasized. The cross-hatched area was bright when viewed with the infrared camera.



Sample	%Water
F	200
G	197
H	1
I	377

Figure 42. Plan view of the John O. Morton Building showing the two wet areas detected by the infrared camera and verified by core samples.

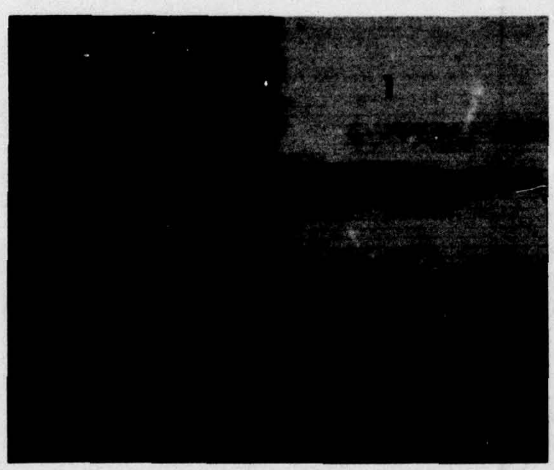


Figure 43. Thermogram of the anomaly that abuts the penthouse (1), showing the location of sample I.

Figure 44. View of the area shown in the Figure 43 thermogram.

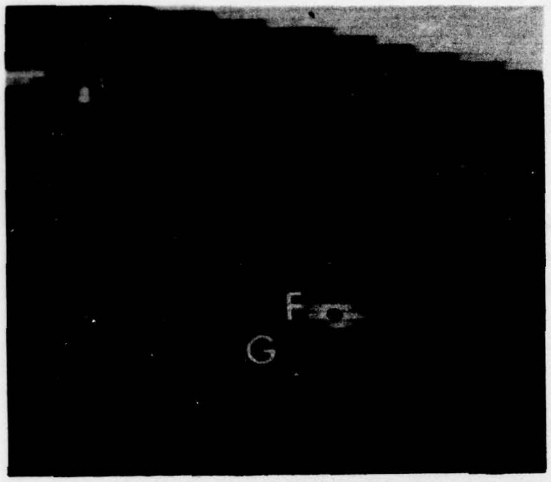


Figure 45. Thermogram of the second anomaly detected on the John O. Morton Building (see Fig. 42 for its location). The objects in the upper left corner of the thermogram are a fan and a vent pipe.

Figure 46. View of the area shown in the Figure 45 thermogram. This photograph was taken after gravel had been removed by CRREL in search of a cause of the wet area. The membrane was found to be cracked all along the denuded area. The crack was widest at point F.

the spray painted boundary shown in Figure 44, the actual replacement should be simplified to a somewhat larger rectangular area. It is possible that the zone of wet insulation may expand before this work is accomplished. Therefore, it is recommended that the extent of replacement be defined so as to achieve removal of all wet insulation uncovered as the work progresses. Penthouse flashing abutting this area should also be removed and replaced.

The second thermal anomaly detected on this roof is shown in Figure 45. A photograph taken of this area is shown in Figure 46. This is an unusual anomaly since it occurs in an undisturbed area of the roof lacking penetrations or flashings. The vast majority of wet spots that have been located with the infrared camera surround drains, vents and other penetrations or abut flashings. On the thermogram (Fig. 45) it can be seen that a white spot exists within the anomaly. This was marked with spray paint and the following day gravel in that area was removed. A wide crack in the membrane was found at that spot. Removal of additional gravel along the extensions of that crack revealed that the crack narrowed but extended from one side of the anomaly to the other (Fig. 46). A sample taken at the bright spot revealed that the membrane crack was directly above a seam in the insulation. The insulation at that location and at position G nearby (Fig. 45 and 46) had water contents of 200% and 197%, respectively.

All that water, if left under the membrane, may also cause problems in other areas when vaporized during warm sunny days. It is doubted that breather vents are capable of removing this moisture. Consequently, it is recommended that the membrane and insulation in the wet area be removed and a new membrane and insulation be installed. As stated previously for the other anomaly located on this roof, the patch should be somewhat larger than the area bounded by the spray painted line and of a less complex shape. Its size should be determined as removal of wet insulation progresses, so as to be sure that all wet materials are removed.

Since this roof is in good condition, it is considered prudent to remove and replace the two wet areas to avoid further deterioration.

DEPARTMENT OF HEALTH AND WELFARE LABORATORY

This building is only a few years old but is suffering from chronic roof leaks. Visually the gravel-covered membrane is in excellent condition. The only visible flaw on the roof is the displaced parapet wall cap flashing in one area (Fig. 47). The location of this problem is shown in the plan view of this roof (Fig. 48). This material should be repositioned as soon as possible.

A comprehensive infrared survey of the roof uncovered three potential problem areas as shown in Figure 48. A thermogram and photograph of the first of these areas are shown in Figures 49 and 50. Insulation samples taken at A and B had water contents of 236% and 32% respectively. The perlite board insulation was

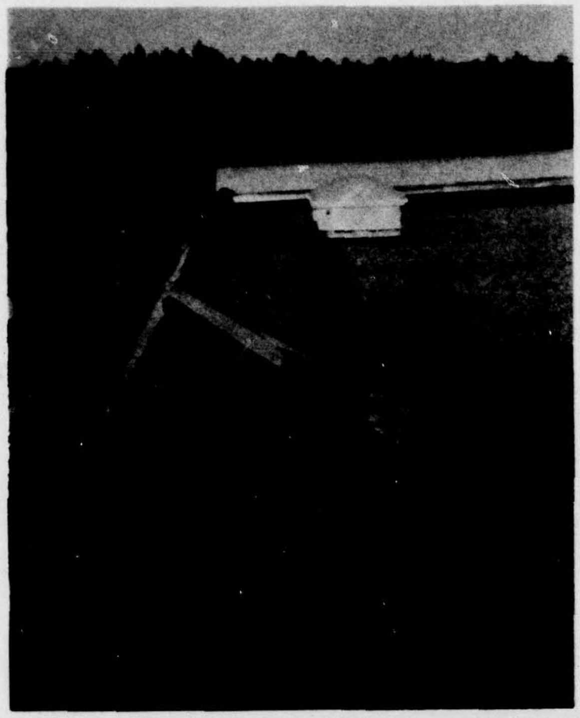


Figure 47. Condition of parapet wall cap flashing on a portion of the Department of Health and Welfare Laboratory.

6½ in. thick at A and 4½ in. thick at B. Over most of the roof the insulation was 2 in. thick. The insulation was extra thick at A and B to provide slope to internal drains and to elevate the perimeter of the roof where problems are likely.

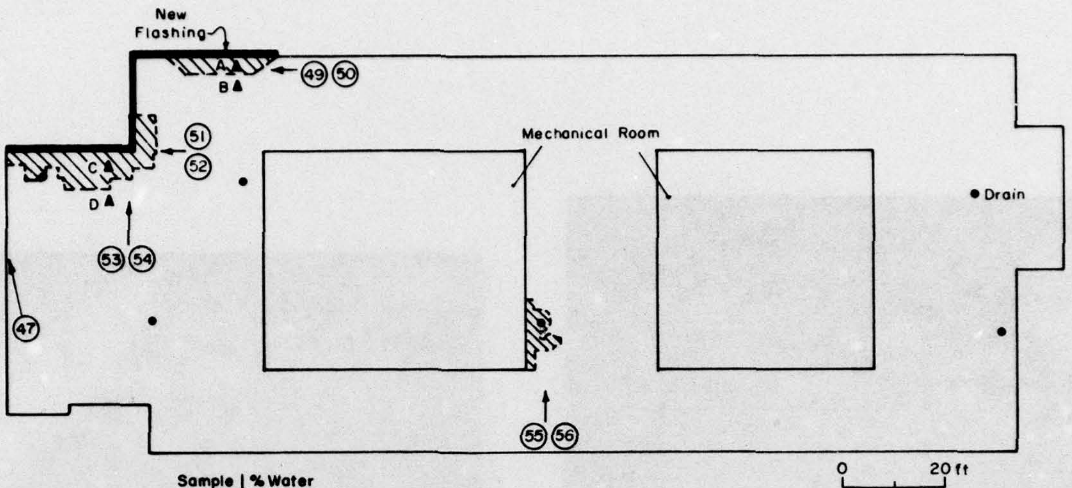
Sometime in the past the copper counter flashing along a portion of this wall was stolen. It is understood that this area remained without counter flashing for over half a year. The bold perimeter in the plan view (Fig. 48) has new copper counter flashing. It is quite likely that moisture entered this area during the period when the counter flashing was missing. Consequently, it is expected that the cause of this problem has been eliminated. Water in the insulation could cause membrane deterioration when it vaporizes in warm weather. Therefore, it is suggested that two breather vents be installed in this area in an attempt to dry out this insulation. There is some question whether this will work, but it is considered worth a try.

The second anomaly detected with the infrared camera was located nearby (Fig. 48). Two views of it are shown in Figures 51-54. Sample C, within the anomaly, had a water content of 380%, while sample D nearby (Fig. 52) had a water content of 3%.

This wet area is also adjacent to the portion of the parapet that had copper counter flashing missing for some time. Since new counter flashing is now in place, no additional water should be entering that area. As with the first anomaly, it is recommended that two breather vents be installed in this area in an attempt to dry out the wet insulation.

The third and final thermal anomaly detected on this roof is shown in Figure 55. Figure 56 is a photograph of the same area. As can be seen in the photograph, a drain is located within the wet area and flashing abuts it. Also an open-ended drain pipe is suspended directly above the drain. No flashing, drain or membrane problems could be detected visually. It is recommended that the gravel cover be removed in this area to expose the membrane which should be examined for flaws. The drain should be disassembled and rebedded in the membrane. The flashing abutting the wet area should be examined in detail and, if possible, removed and replaced. A breather vent should be installed in an attempt to dry out this area and then a protective gravel cover added to complete the job.

As an alternative to the above, the membrane, insulation, flashing and drain in the wet area could be removed and replaced as was recommended for the two wet areas of the John O. Morton Building.



Sample	% Water
A	236
B	32
C	380
D	3

Figure 48. Plan view of the Department of Health and Welfare Laboratory.

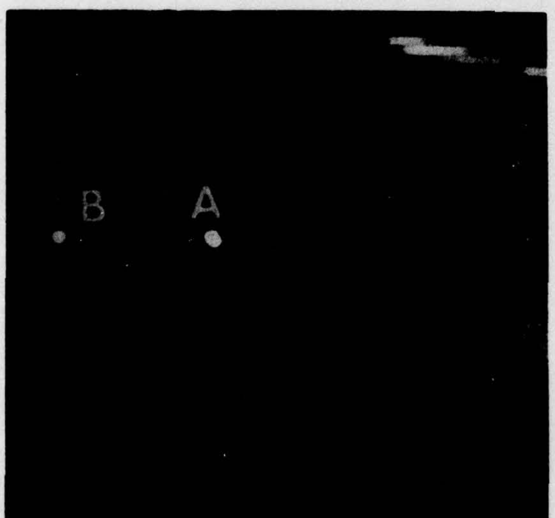


Figure 49. Thermogram of an anomaly along the parapet wall.

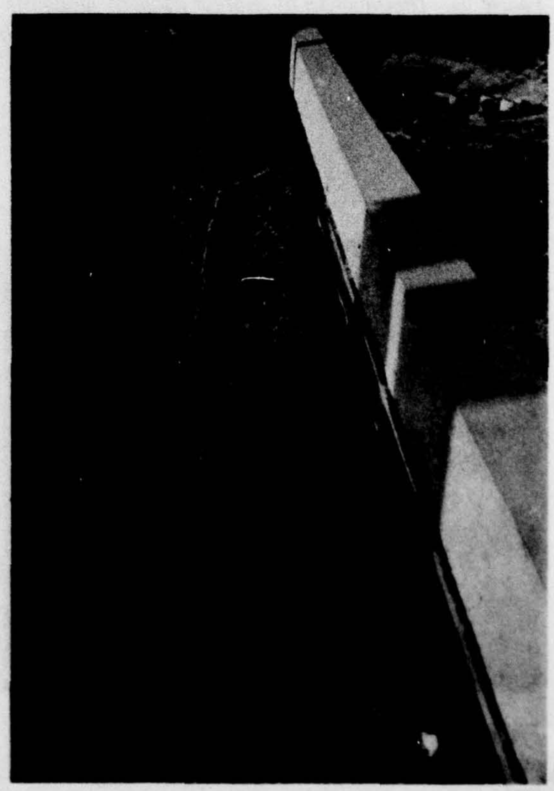


Figure 50. View of the area shown in the Figure 49 thermogram.

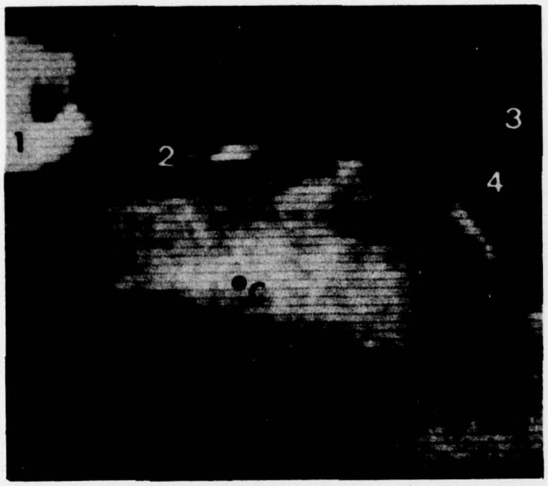


Figure 51. Thermogram of another anomaly along the parapet wall (1 – fan, 2 – drain, 3 – parapet, 4 – flashing).

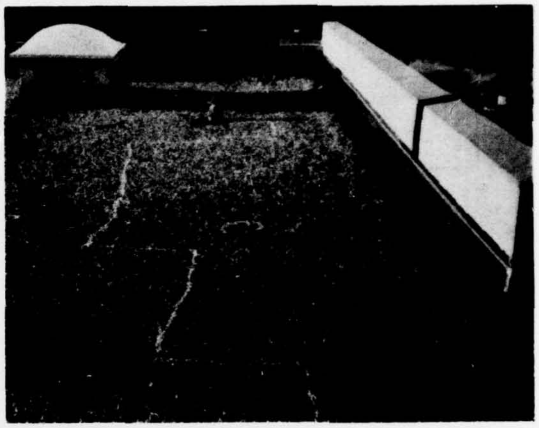


Figure 52. View of the area shown in the Figure 51 thermogram.

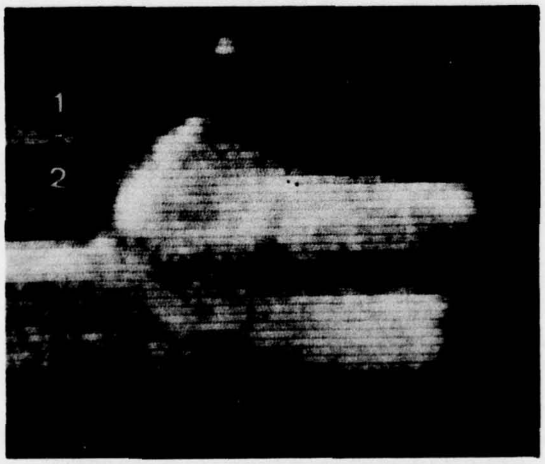


Figure 53. Thermogram of another portion of the anomaly shown in Figure 51 (1 – parapet, 2 – flashing).

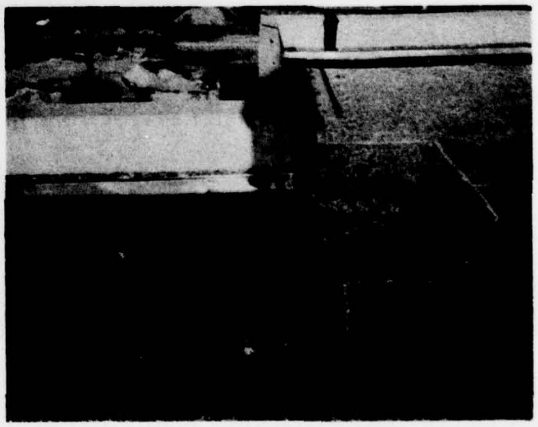


Figure 54. View of the area shown in the Figure 53 thermogram.

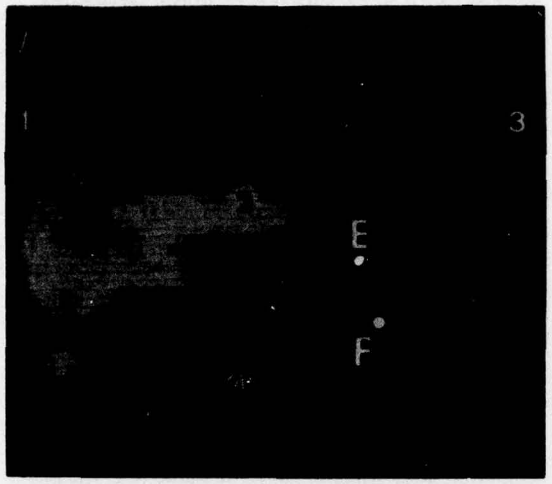


Figure 55. Thermogram of the anomaly adjacent to a mechanical room (1 — flashing, 2 — roof drain, 3 — support for mechanical equipment).

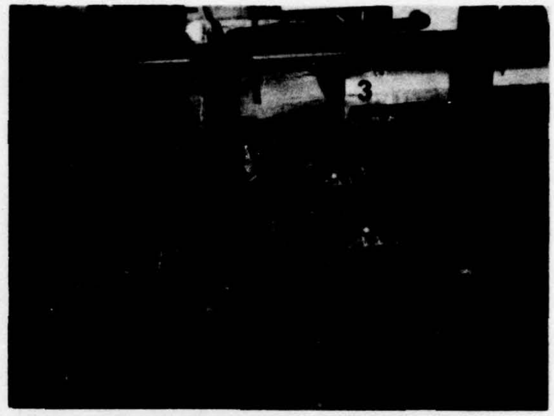


Figure 56. View of the anomaly shown in the Figure 55 thermogram (1 — outfall of drain pipe 8 in. above roof drain, 2 — roof drain, 3 — support for mechanical equipment).

ECONOMICS OF ROOF REINSULATION

Several of the older State buildings have uninsulated roofs, and other vintage roofs have minimal insulation. Heat losses through the roofs of these buildings are very high relative to current recommendations and standards (ASHRAE 1975). Unfortunately, newer buildings also contain significantly less than optimal roof insulation considering today's high energy costs. It is believed that life-cycle economic studies would indicate that more roof insulation can be justified for new buildings in Concord, New Hampshire, than is currently installed. The State is urged to conduct such studies for all new buildings, for buildings under construction, and for any building when reroofing is necessary for other reasons.

The annual heat loss through a roof depends on the length and severity of cold weather, the temperature maintained within the heated space and the thermal resistance of the roof. NOAA (1976) indicates that over the past 30 years the heating season in Concord, New Hampshire, has averaged 242 days. During the heating season the average outside temperature is 36°F. A reasonable assumption for the temperature on the warm underside of the roof is 75°F. Therefore, a temperature difference of 75° – 36° = 39°F is maintained for 242 days (5808 hours) annually.

The amount of heat lost annually per square foot of roof is equal to the 39°F average temperature difference multiplied by the 5808 hours over which that average difference is maintained and divided by the thermal resistance, R, of the roof. For Concord, New Hampshire, the annual heat loss in Btu per square foot is then 39°F (5808 hr)/R = 226,512/R where R is in ft^2 hr °F/Btu. The annual heat loss in MBtu* per square foot equals 0.226512/R.

The annual fuel cost per square foot is then the product of the fuel cost per MBtu multiplied by (0.226512/R).

The State House, State House Annex, Legislative Office Building and State Library are heated by steam. From information obtained from State personnel, it was determined that the average cost of steam delivered to these buildings during the 75-76 winter was \$4.08/1000 lb. Since the steam is produced at 60 psig and the condensate leaves the building at about 150°F, 1060 Btu/lb are used. The relationship between annual fuel cost per square foot in Concord, New Hampshire, and thermal resistance is shown in Figure 57 for fuel costs of \$2.50, \$3.00, \$3.50 and \$4.00 per MBtu.

The thermal resistance of the wet insulation on the library roof was measured by Tobiasson and Dudley (1977). To their average value of R = 6.9 ft^2 hr °F/Btu should be added R = 0.8 to account for inside and outside skin resistances. The total R equals 7.7 for this roof. From Figure 57, the annual cost of energy lost through this roof, based on those heat flux readings and a fuel cost of \$3.85/MBtu, is \$0.12/ft^2.

Means (1976) indicates that the cost of removing deteriorated roofing and insulation is about \$0.45/ft^2 and the cost of installing insulation with R = 8 and a new membrane is about \$1.24/ft^2. If R = 16 the new

* MBtu = million Btu.

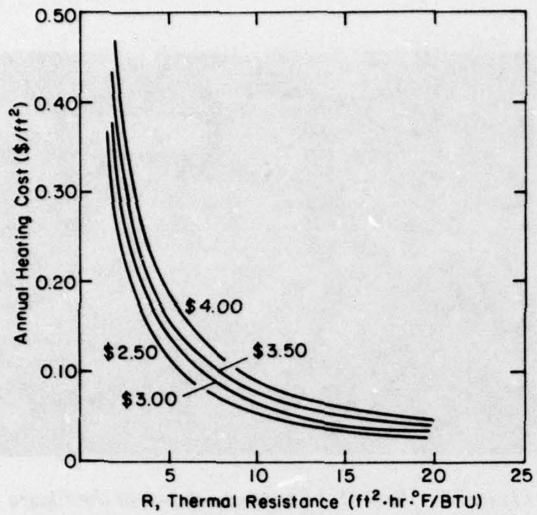


Figure 57. Curves that relate heating costs to thermal resistance for various fuel costs ($/MBtu) for Concord, New Hampshire.

insulation and membrane would cost an estimated $\$1.74/ft^2$. Total costs to remove and replace would then equal $\$1.69/ft^2$ (R = 8) and $\$2.19/ft^2$ (R = 16). ASHRAE (1975) recommends R = 16 for roofs of nonresidential buildings in Concord, New Hampshire.

According to Figure 57, increasing the thermal resistance of the roof from R = 7.7 existing to R = 16 would decrease first year fuel costs (at $3.85/MBtu) from $\$0.12/ft^2$ to $\$0.06/ft^2$ thereby saving $\$0.06/ft^2$.

If it is assumed that the annual rate of cost increase of fuel equals the interest rate, the number of years required to pay off the capital debt for the new roof by savings realized in fuel costs equals the capital cost divided by the first year's annual fuel saving (Griffin 1974). It is likely that the annual cost increase for fuel will exceed the interest rate during the next decade. In that case, the capital debt will be paid off somewhat sooner (e.g. the financial incentive to provide additional insulation will be even greater). Griffin (1974) describes how to conduct economic studies which consider increasing fuel costs and varying interest rates. In this report the simplifying assumption has been made that the annual fuel cost increase equals the interest rate. For the example above, the $\$0.06/ft^2$ saved the first year by increasing the thermal resistance to R = 16 results in a $2.19/0.06 or a 36-year payback period for the $\$2.19/ft^2$ investment in new materials.

Generally the high cost of replacing an old roof having minimal insulation with a new well-insulated roof cannot be justified by energy conservation alone. However, if it is acknowledged that the membrane must be replaced because it is no longer serviceable, then only the cost of the new insulation need be included in the payback analysis.

Using material and labor costs from Means (1976), an incremental cost analysis was generated for one type of insulation. Results are presented in Table I.

This information is intended to represent typical results of an incremental economic study. The numbers are nationwide generalities and may require refining by local cost factors and experience before final economic decisions are made. Table I clearly indicates that several inches of insulation should be installed since the extra costs associated with several successive increments can be recouped in a reasonable amount of time by the fuel savings expected.

Table I also indicates that the first increment of insulation installed is the most valuable (e.g. the payback time for the first inch of polystyrene is 1.3 years; for the second inch, 3.6 years; for the third inch, 12.1 years; for the fourth inch, 13.8 years; and for the fifth inch, 28 years). Since the Library is a permanent building that will be in use for many years, a 13.8-year payback period on the last increment installed seems reasonable. Since built-up roofing seldom lasts more than 20 years, it seems inconsistent to invest in insulation that takes longer than 20 years to pay for itself. Therefore, if polystyrene insulation is chosen, 4 in. is recommended.

The insulation presented in Table I was selected to illustrate the method of incremental economics. Several other insulations are available that should also be considered. Independent of which insulation is selected, it is obvious that the installation of a significant amount of thermal resistance (R = 15 to 20) can be justified when a roof membrane is replaced in the Concord, New Hampshire, area.

Economic studies can be conducted for other buildings once the net fuel cost for each is known. State personnel indicate that during the 1975-76 winter the average cost of fuel oil varied among buildings as follows:

John O. Morton Building	$0.301/gallon
Supreme Court	0.307
Dept. of Health and Welfare Lab.	0.279
Fish and Game Offices	0.330
Highway Garage	0.341.

Using a fuel heat content of 140,000 Btu/gallon and allowing for an efficiency of 70%, the net energy in a gallon of fuel oil is 98,000 Btu.

The cost of fuel oil per MBtu is then:

John O. Morton Building	$3.07
Supreme Court	3.13
Dept. of Health and Welfare Lab.	2.85
Fish and Game Offices	3.37
Highway Garage	3.48.

Table I. Incremental economic study.

	R*	Total R	ΔR	Capital cost†	$\Delta\$$ capital	Annual fuel cost†	$\Delta\$$ fuel	Payback time**
Existing roof	2.0	2.0		0	0	$0.42		
Expanded polystyrene								
First inch	3.6	5.6	3.6	$0.34	$0.34	0.161	$0.26	1.3
Second inch	7.2	9.2	3.6	0.56	0.22	0.100	0.061	3.6
Third inch	10.8	12.8	3.6	0.90	0.34	0.072	0.028	12.1
Fourth inch	14.4	16.5	3.6	1.12	0.22	0.056	0.016	13.8
Fifth inch	18.0	20.0	3.6	1.46	0.34	0.044	0.012	28.0

* R = ft² hr °F/Btu.
† Capital and fuel costs are in \$/ft². Capital costs are from Means (1976). Fuel costs are from Figure 57.
** Payback time (years) = Δ\$ capital/Δ\$ fuel (assuming annual increase in fuel cost = interest rate – see Griffin 1974).

The thermal resistance of the Department of Health and Welfare Laboratory roof was measured at $R = 5.1$ (Tobiasson and Dudley 1977). Adding $R = 0.8$ to account for inside and outside skin resistances, the total R equals 5.9. From Figure 57 with $R = 5.9$ and a fuel cost of \$2.85/MBtu, the annual cost of energy consumed by this roof is \$0.109/ft². A new well-insulated roof ($R = 16$) would reduce the annual fuel cost to \$0.04/ft². However, this would only save \$0.069/ft² the first year. Since the cost of replacing this roof with such a new roof would be about \$2.19/ft², the payback time would be about 32 years. It is obviously uneconomical to perform such work for energy conservation purposes alone. Since the membrane of the existing roof is in good condition, it should not be disturbed. This conclusion also applies to the roof of the John O. Morton building.

The two examples discussed above illustrate the previous point that the cost of tearing up existing insulation and a membrane in good condition to better insulate a roof generally cannot be justified by energy conservation alone. The Highway Garage provides an exception to this generality.

The Highway Garage has a complex heating system partially fueled with propane and partially with oil. During the 1975-76 winter, propane provided 42% of the energy and oil the remaining 58%. State personnel indicated that the cost of the propane was \$2.19/MBtu. Applying a 75% efficiency to the propane system, the net of that fuel equals \$2.92/MBtu. Since the fuel oil used in the Garage cost \$3.48/MBtu, the combined cost of the 42% propane–58% fuel oil system was \$2.92 (0.42) + \$3.48 (0.58) = \$3.24/MBtu.

Heat flux and temperature measurements by Tobiasson and Dudley (1977) indicate that the portions of the Highway Garage roof insulated with light-weight concrete have an R equal to 2.2. Adding $R = 0.8$ for inside and outside skin resistances, the total R equals 3.0. From Figure 57 using $R = 3.0$ and a fuel cost of \$3.24/MBtu, the current cost of heat escaping through this roof is \$0.25/ft². A new well-insulated roof ($R = 16$) could reduce the current heating cost to about \$0.045/ft², thereby saving \$0.205/ft² the first year. If such a roof cost \$2.19/ft² to install, it appears that in about 10.5 years the fuel savings would pay for the new membrane and insulation.

Although the Highway Garage roof is apparently not leaking, it contains damp or wet insulation in several areas. It appears economically opportune to remove the existing membrane and add insulation in the near future.

The thermal resistances of the State House and State House Annex roofs have not been measured. Neither roof contains insulation per se. Perhaps, like the Highway Garage, replacement insulation can be justified by energy conservation alone. However, since the roof membrane on the State House is in good condition, it would be a lower priority roof to replace than that of the Highway Garage. Since the State House Annex roof membrane is aged and in need of replacement, work there is considered to be of relatively high priority.

CONCLUSIONS AND RECOMMENDATIONS

The infrared survey and the water content measurements of samples of wet and dry insulation have defined problem areas on several roofs. This information together with thermal resistance measurements by Tobiasson and Dudley (1977) and the economic study in this report should permit the State to establish priorities for a cost-effective roof repair program and

justify the need for funds to replace deteriorated and thermally inefficient roofs.

The highest priority for replacement is the *Library* roof. All the insulation on that roof is damp or wet and the membrane is dry, brittle, delaminated and blistered. Since the concrete deck is also wet, it will be important to ventilate any new system to prevent trapped moisture from destroying the new membrane. The economic study presented in this report indicates that the new roof system should have a thermal resistance $R > 15$. Major improvements to better seal the skylights will be required in conjuction with the new roofing.

There is no insulation above the concrete roof of the *State House Annex*. Portions of the membrane are dry and brittle with numerous flashing problems. Although leaks are apparently not a problem, moisture is present under the membrane and the deck is damp in places. Because of the poor condition of the existing membrane, a new membrane can be justified in the near future. At that time, insulation should be added to provide this roof with $R > 15$. The new roofing should be designed to ventilate moisture trapped in the concrete deck.

The roof of the *State House* is also uninsulated. Perhaps replacement of insulation can be justified by energy conservation alone, but since the membrane is in relatively good condition, this is a lower priority item than the Library roof or the Annex roof.

Levels 1 and 3 of the *Highway Garage* roof contain wet light-weight concrete insulation and have a very low thermal resistance. Breather vents installed on this roof a few years ago show no sign of being able to dry the wet insulation. Although those roofs received a new membrane a few years ago, it appears economically attractive from an energy conservation perspective to remove this membrane, install provisions to dry the light-weight concrete, and then add additional insulation to achieve $R > 15$ and a new membrane. A 10-year payback is expected.

Level 2 of the Highway Garage appears to be somewhat better insulated than levels 1 and 3. No work is recommended there until such time as membrane deterioration necessitates replacement. At that time additional insulation should be added.

Portions of the level 4 roof of the Highway Garage contain wet insulation and in one area no insulation is present. The existing thermal resistance of the level 4 roof is estimated to be somewhat lower than the measured value of $R = 2.2$ on level 1. If this is the case, the installation of new well-insulated roofing ($R > 15$) can be justified on level 4 by energy conservation alone. Since this roof contains wet insulation, it should receive a relatively high priority.

No moisture problems were detected on the roof of the *Public Health Complex* or the *Legislative Office Building*. Movement of the metal fascia on the Legislative Office Building has split the mastic at joints. Repairs should be made to prevent deterioration of this roof.

The roof membrane on the *Fish and Game Offices* is in poor condition and will need to be replaced before long. All insulation is below the wood deck between wood joists. Vapor control on the warm side of that insulation is inadequate and should be improved. When the membrane is replaced, some insulation should be added above the wood deck to provide a better substrate for the new membrane and to provide slope for drainage.

The hot area detected by the infrared camera on the *Supreme Court* roof should be examined in detail from within the building by State maintenance personnel to determine if a leak has wetted the wood deck and frame.

Two small thermal anomalies were found with the infrared camera on the roof of the *John O. Morton Building*. Samples verified that the insulation was wet in these areas. It is recommended that, as soon as possible, the insulation and membrane in these two small areas be removed and replaced with dry insulation and a new membrane. Flashing that abuts one of these wet areas should also be removed and replaced. Solving these two little problems will prevent rapid deterioration of the rest of the roof.

Three small wet areas were located with the infrared camera on the roof of the *Department of Health and Welfare Laboratory*. At two of the three locations, the missing counter flashing that apparently allowed water to enter the roof has been replaced, solving the root cause of the problem. Since the water that has entered the perlite board insulation could cause progressive membrane deterioration, the moisture should be removed. As an inexpensive experiment it is suggested that breather vents be installed at these two locations in an attempt to dry this insulation. The third anomaly on the roof of the Department of Health and Welfare Laboratory is located at a drain and near flashing. As no visible flaws were detected, it is recommended that the area be cleared of gravel, the drain disassembled and the abutting flashing removed to locate the leak. The area should then be repaired. The installation of a breather vent is suggested as a potential means of drying the wet insulation.

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